QUANTUM WELL DETECTOR WITH LAYER FOR THE STORAGE OF PHOTO-EXCITED ELECTRONS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The field of the invention is that of electromagnetic wave detectors made with III-V semiconductor materials so as to define quantum well structures.

The working of such detectors is based on the occurrence of electronic transitions between permitted energy levels (e_1 and e_2) within the conduction bands of semiconductor quantum structures. Figure 1a gives an example of this type of transition in a well having two discrete permitted energy levels for the electrons. By applying an electrical field to this type of configuration, it is possible to extract electrons from the well in giving preference to the electrons located at the second quantum level. Thus, through the collection, in the external electrical circuit, of these electrons coming from the second quantum level to which they have been carried by an illumination hv , it is possible to detect this illumination.

To achieve high absorption of the illumination to be detected, it is possible to use a large number of wells within detectors based on this quantum principle. Figure 1b shows a multiple-well configuration of this kind.

The problem encountered with the prior art structures, described here above, lies in the high rate of carrier recombination. This is due especially to a barrier layer between successive wells. This barrier layer has a small thickness which is close to that of the quantum wells.

Photovoltaic variants of these detectors have been proposed in the literature [see Borge VINTER, "Detectivity of a three-level quantum well detector", IEEE Journal of Quantum Electronics, Vol. 30, p. 115 (1994)].

The problem encountered with prior art structures, as described here above, lies in the high rate of carrier recombination.

This recombination restricts the performance characteristics of these detectors and especially their operating temperature.

In the case of the photovoltaic device, this limitation is due to an excessively thin barrier layer between the two neighboring wells constituting the photovoltaic structure.

To place substantial limits on the recombination rate of the carriers, the invention proposes the introduction, in the detector, of a storage layer different from the absorbent layer (quantum well), and to do so by means of a transfer barrier with a great width as compared with that of the quantum well. By thus separating the absorption function (in the quantum well) and the photocarrier read function (in a storage layer), the performance characteristics of the detectors are improved through prevention of the recombinations of carriers.

To enable the flow of the photo-excited electrons in a storage layer, the transfer barrier has a conduction potential profile that shows a decrease starting with the quantum well.

SUMMARY OF THE INVENTION

More specifically, an object of the invention is an electromagnetic wave detector comprising a stack of layers made of III-V semiconductor materials, the conduction band profile of said materials defining at least one quantum well, said quantum well having at least one first discrete energy level populated with electrons that are capable of passing to a second energy level under the absorption of an electromagnetic wave and means for the reading of said electrons in the second energy level wherein the stack of layers of semiconductor materials furthermore comprises an electron storage layer separated from the quantum well by a transfer barrier layer, the thickness of the transfer barrier layer being about one order of magnitude greater than the thickness of the quantum well, the lower energy level of the conduction band of the transfer barrier layer being greater than those of the quantum well and the electron storage layer and decreasing from the quantum well to the electron storage layer so as to further the flow of electrons from the second energy state to the electron storage layer.

Thus, the detector of the invention comprises:

- a quantum well having an intersubband absorption at the desired energy, this layer being quite similar to the quantum wells commonly used in the quantum well detectors [B. LEVINE, "Quantum well infrared photodetectors", Journal of Applied Physics, Volume 74, No. 8, R1. (1993)];

- a transfer barrier that behaves like a loss of potential in which the photo-excited electrons may be transferred;

- a layer for the storage of the photo-excited electrons;

- means for reading the photosignal.

According to a first variant of the invention, the transfer barrier may consist of a semiconductor alloy whose composition varies along the thickness of said barrier so that the conduction potential decreases with distance from the well.

According to a second variant of the invention, the transfer barrier may be made out of piezoelectric material that generates a natural electrical field, enabling the conduction potential of the transfer barrier to be given the required profile.

According to a third variant of the invention, the semiconductor structure may also be placed directly under an electrical field to obtain the desired conduction potential profile for the transfer barrier.

Furthermore, the reading of the photodetection signal may be done differently.

It may relate, for example, to a measurement of parallel photocurrent using ohmic contacts that contact the storage layer without contacting the absorbent quantum well.

It may also be a photovoltaic reading of the voltage due to the spacing between the electrons in the storage layer and the layer of the absorbent well.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be understood more clearly and other advantages will appear from the reading of the following description, given by way of a non-restricted embodiment with reference to the appended figures, of which:

- Figure 1a gives a schematic view of an electromagnetic wave detection device comprising a quantum well, according to the prior art;
- Figure 1b gives a schematic view of a multiple quantum well structure used in prior art detection devices;
- Figure 2 illustrates a stack of semiconductor layers used in a detector according to the invention;
- Figure 3 illustrates the profile of the conduction bands of the stack of layers mentioned above;

- Figure 4 illustrates a first example of means for the reading of photo-excited electrons in a measurement of parallel photocurrent in a detector according to the invention;
- Figure 5 illustrates a second example of the means of reading photo-excited electrons in a measurement of parallel photocurrent in the detector according to the invention;
- Figure 6 illustrates the modified profile of the conduction bands of the stack of layers illustrated in Figure 3, taking account of the space charge effects; the modification of this profile comes from the transfer of a population of electrons from the quantum well to the storage layer;
- Figure 7 illustrates an exemplary means for the reading of the photo-excited electrons in a photovoltaic measurement in a detector according to the invention;
- Figure 8 illustrates a detector according to the invention comprising reading means in a measurement of parallel photocurrent and means for the resetting of the detector;
- Figure 9 illustrates a second exemplary conduction band used in a stack of layers of a detector according to the invention;
- Figure 10 illustrates a third exemplary conduction band profile used in a stack of layers of a detector according to the invention;
- Figure 11 illustrates a fourth exemplary conduction band profile used in a stack of layers of a detector according to the invention.

MORE DETAILED DESCRIPTION

In general, the detector according to the invention comprises a stack of semiconductor layers comprising especially as shown in Figure 2:

- a substrate 1;
- a first barrier layer 2 to confine the electrons in the quantum well;
- a constituent layer of the quantum well 3;
- a second barrier layer 4 that is a transfer barrier layer with an inclined conduction band profile;
- a layer 5 for the storage of photo-excited electrons;

- a third barrier layer 6.

Figure 3 illustrates the conduction band profile of the above-mentioned stack of layers.

Typically, there is an order of magnitude between the width of the quantum well l_q and the width of the transfer barrier l_b to prevent possible recombinations of the photo-excited electrons.

Indeed, the transfer barrier may be very thick, as the electrons captured in the storage layer remain there for a very long time (from periods ranging some µs to some ms). Indeed, the carriers take very long to return to equilibrium in the quantum well by tunnel effect in passing through the very thick transfer barrier (it is possible to chose a thickness of several hundreds of nanometers if desired). The gain in photoconductivity is therefore very high if we compare this time with the lifetime of the photo-excited electrons in the standard quantum well detectors (in the range of 1 ps).

To read the photodetection signal, it is possible to use two methods that we shall describe here below.

1st method: measurement of the parallel photocurrent

This measurement is made in the plane of the electron storage layer. For this purpose, first and second ohmic contacts make contact with the storage layer without contacting the absorbent quantum well as shown in Figure 4 which again shows the stack of layers of semiconductor materials shown in Figure 2. Figure 4 also shows the ohmic contacts C_1 and C_2. The arrows illustrate the routing of the electrons and their flow from the quantum well 3 to the storage layer 5 in which they are collected by means of the contacts C_1 and C_2. This assumes that the thickness of the transfer barrier is great enough for the diffusion of the ohmic contact to make contact with the storage layer without reaching the absorbent quantum well. This photocurrent is parallel to the number of electrons captured and the time for reading it is very long if compared with the standard quantum well detectors. Since the storage layer is not doped, the current is very weak without illumination of the structure since this layer contains very few carriers in a state of thermodynamic equilibrium. The illumination of the structure sends

electrons to the excited level E_2 of the absorbent quantum well. A part of these electrons travel to the storage layer through the transfer barrier. The conductivity of the storage layer then increases enormously. Thus, at a conceptual level, there is an optically controlled transistor: the storage layer is the channel, the role of the gate is fulfilled by the optical beam to be detected and the source and the drain are the two electrodes between which the photocurrent is read. It must be stressed here that it is vitally important for the ohmic contacts not to reach the absorbent layer. There are known ways, by the diffusion of dopants, to make contacts that reach the storage layer without touching the absorbent well for a transfer barrier, between the two layers, having a thickness as fine as 500 Angstroms.

Another geometry of contacts consists in making a mesa by a technology that is quite standard, and then contacting the storage layer beneath the quantum well. In this case, during the growth, the order of the layers has been reversed with respect to the previous approach. This approach has the advantage of not requiring control over the depth of the contact. The drawing is shown in Figure 5 wherein the optically controlled transistor function appears more clearly.

Estimation of the photocurrent at the end of 10 ms storage:

With a typical flux of 10^{16} photons.cm^{-2}.s^{-1}, and an absorption of 5% in the unique quantum well (this is a common value for a quantum well provided with a surface diffraction grating), approximately 5.10^{14} electron per cm^2 and per second are placed at the level E_2 (excited state). Assuming that there is a probability of 1/2 that an electron will leave the transfer barrier and reach the storage layer (against a probability of 1/2 that it will fall back on the fundamental level of the well and therefore be of no use for the photodetection), this gives, in 10 ms of integration time, $2.5.10^{12}$cm^{-2} electrons transferred into the storage layer.

In reality, this model is far too simplistic and it is necessary to absolutely take account of the space charge effects in this structure where the electrons are transferred far from the dopant atoms. The space charge effects lead to a field induced in the transfer barrier and this barrier stops transferring the carriers when this induced field compensates for the loss of

potential that naturally exists in the transfer barrier. Because of these space charge effects, the band structure is deformed and goes from the one shown in Figure 3 to the one shown in Figure 6.

To compute the maximum number of carriers transferable in the storage layer, the equilibrium between the field due to the space charge effects and the potential slope in the transfer barrier is written without transferred carriers. For a barrier like that of Figure 2, this leads to a potential slope equal to 180 meV/500 Å = 36 kv/cm.

The field due to the space charge effects is equal to $E = \rho_S e/\varepsilon_0\varepsilon_r$, where ρ_S is the density of transferred electrons. By equalizing the two quantities, it is deduced that ρ_s is about $2.5\ 10^{11}\ cm^{-2}$.

In view of the above computations, it can be seen that the storage layer has been filled at the end of an integration time of about 500 µs for the illumination levels given here above.

The storage layer then has an electrical resistance (for a standard pixel surface area used in the detectors, equal to 30 µm*30 µm) of R = L/NqµS 250 Ω. For this purpose, the value of mobility taken is $\mu = 10^5\ cm^2\ V^{-1}s^{-1}$, which is current for GaAs transistor canals at 77 K. This resistance, which is very low, therefore corresponds to a 40 µA photocurrent for a bias of 1 mV between the source and the drain. These photocurrents are much greater than the photocurrents of the usual quantum well detectors owing to the increase in the gain of photoconductivity.

<u>2nd method: photovoltaic measurement</u>

In this case, a measurement is made of the voltage due to the spacing between the electrons in the storage layer and the layer of the absorbent well, which is doped, and this is done by means of two ohmic contacts taken respectively at the level of the storage layer (contact C'_1) and the level of the quantum well (contact C'_2) as shown in Figure 7. A direct reading is made of the voltage which will range from 0 to 180 mV in the case of a barrier whose percentage of Al varies from 30% to 8% in an $Al_xGa_{1-x}As$ alloy. It must be noted that the maximum value of the voltage does not depend on the width of the storage layer. The effect of this width is above all the modification of the time of return to equilibrium by the electrons.

The maximum voltage of 180 mV (i.e. at saturation) will be measured for a typical flux of 10^{16} photons.cm^{-2} during an integration time of about 500 µs. An integration time of 30 ms makes it possible to obtain a voltage of 180 mV for a very low photon flux: 2.10^{14} photons.cm^{-2} only.

This type of detector will therefore be particularly well suited to detection in a spectral zone where there are few photons, such as the 3-5 µm zone for the infrared imaging of black bodies at 300 K.

The higher detectivity of this type of photovoltaic detector as compared with the quantum well photovoltaic detectors described earlier in the literature [B. VINTER, "Detectivity of a Three-Level Quantum Well Detector", IEEE Journal of Quantum Electronics, Vol. 30, p. 115 (1994)] results from two specific advantages.

1) An efficient capture rate in the storage layer: a high proportion of the carriers (for example half of them) are transferred to the storage layer through the potential slope present in the barrier layer. This potential slope herein plays a crucial role: it is this layer that makes it possible to have efficient transfer. Indeed, through this potential level, the electrons cannot rise and return, and cannot get recombined in the absorbent wells.

2) A lengthy time of return to equilibrium: the transfer barrier is very thick (for example 500 A) thus increasing the time of return of the carriers from their metastable level in the storage layer to their state of equilibrium in the quantum well. The gain is thus increased.

In any case, a perpendicular voltage may be applied to the device to force the electrons to return to the absorbent quantum well if it is desired to initialize the system between two measurements.

In the case of the first photoconductive reading method, it is necessary to add two n+ doped layers, 1' and 6' to the stack of layers (2 → 6) illustrated in Figures 4, 5, and 7, one on the top of the structure and the other below it. This then gives a four-contact device C_1, C_2, C_3, C_4 as shown in Figure 8.

In the case of the second photovoltaic reading method, it is possible to stay with the drawing of Figure 7, and only two contacts are kept. Two contacts are used for the reading of the voltage and for initializing the system.

This initializing principle may be used during the reading to set the number of electrons in the storage layer at the desired level. This makes it possible for example to set the potential energy in the storage layer with an offset such that the population of electrons is small under a given illumination. Through this offset, the detector reads only the variations of illumination with respect to the mean level of illumination. This is very valuable when the detector analyzes an average infrared scene at ambient temperature.

It must be reported that a certain number of possibilities may be used with the detectors described herein. They have not been described because they are not characteristic of the invention. We might simply cite the diffraction gratings etched on the top of the detector to couple the incident light at the intersubband transition of the absorbent well and thus obtain maximum absorption. (This is a very standard method in the literature.)

A more detailed description shall now be given of exemplary stacked structures that can be used in detectors according to the invention.

The first example of a stack of semiconductor layers that can be used in the invention is the one whose conduction band profile corresponds to the one shown in Figure 3.

This is a configuration in which the transfer barrier is constituted by an alloy whose composition varies along the thickness to obtain the desired profile of the conduction potential of the transfer barrier.

According to this example

- the substrate 1 is made of GaAs, for example non-doped;
- the barrier layer 2 is made of $Al_{0.44}Ga_{0.56}As$ with a thickness of 300 Å;
- the quantum well; having two discrete energy levels E_1 and E_2, is made of $In_{0.15}Ga_{0.85}As$ and typically has a thickness lq = 30 Å;
- the transfer barrier is made with the alloy $Al_yGa_{1-y}As$ having a thickness of 500 Å, the percentage therein varying linearly from 0.3 to 0.08, starting with the quantum well, making it possible to obtain a drop in potential varying from 250 meV to 70 meV in relation to the bottom of the GaAs conduction band;

- the storage layer 5 is made with GaAs and has a thickness of 150 Å;
- the layer 6 is made of $Al_{0.44}Ga_{0.56}As$ identical to the first barrier layer 2.

Thus, during an absorption to be detected, related to an optical transition, the electrons located on the energy level E_1 pass to the energy level E_2 and are then discharged through the transfer barrier into the storage layer in which they may accumulate.

In this example, the quantum well has a second discrete energy level E_2. It is also possible to use a structure in which the quantum well has only one discrete energy level. The optical transition can then take place between the energy level E_1 and the continuum of levels above the barrier as is known in the prior art.

The following is the second example of a stack of semiconductor layers

The detector can be obtained with a stack of semiconductor layers comprising a semiconductor material in which there naturally prevails an electrical field of piezoelectric origin. For example, a material of this kind may be formed by a quantum well made of $In_{0.2}Ga_{0.8}As$ on a GaAs substrate (111). The piezoelectric field present in the quantum well, which is about 100 kV/cm, results in the appearance of an electrical field also in the barriers, as can be seen in Figure 9 showing the following stack of layers used in a second exemplary detector:

substrate 1: GaAs (111)
barrier layer 2: $Al_{0.44}Ga_{0.56}As$ and thickness = 500 Å
quantum well 3: $Ga_{0.8}In_{0.2}As$ with lq = 40 Å
transfer barrier 4: $Al_{0.22}Ga_{0.78}As$ thickness = 500 Å
storage layer 5: GaAs ls = 100 Å
barrier layer 6: $Al_{0.44}Ga_{0.56}As$ and thickness = 500 Å

The following is the third example of stacking of semiconductor layers whose conduction band profile is shown in Figure 10.

The stack of semiconductor layers of the invention is inserted between two ohmic contact layers to apply a voltage V that makes it possible to give the required profile to the transfer barrier. According to this example, there is therefore the following stack of semiconductor layers:

substrate 1 : GaAs

Contact layer 1' : GaAs n+ doped thickness = 3 000 Å

Barrier layer 2 : $Al_{0.44}Ga_{0.56}As$ thickness = 500 Å

Quantum well 3 : $In_{0.15}Ga_{0.85}As$, lq = 35 Å

Transfer barrier layer 4 : $Al_{0.22}Ga_{0.78}As$. l_b = 500 Å

Storage layer 5 : GaAs thickness = 100 Å

Barrier layer 6 : $Al_{0.44}Ga_{0.56}As$ thickness = 500 Å

Contact layer 6' : GaAs n+ doped, thickness = 1 000 Å

The following is the fourth exemplary stack of semiconductor layers whose conduction band profile is shown in Figure 11.

This exemplary stack of semiconductor materials comprises a constituent material of the transfer barrier formed by an alloy whose composition varies and in which the transport of the electrons can be done through the valleys X as shown in Figure 11. This type of behavior is obtained especially with an alloy of $Al_xGa_{1-x}As$ for which the percentage x increases from 0.44 to 1. In this case, the level of the valleys X in the material drops by about 320 meV in the material $Al_{0.5}Ga_{0.5}As$ to about 200 meV in the material AlAs as compared with the bottom of the conduction band. In this example, the substrate, the quantum well barrier layers and the storage layer may be identical to those of the example 1.